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Future changes in Yuan River ecohydrology: Individual and cumulative impacts of climates change and cascade hydropower development on runoff and aquatic habitat quality

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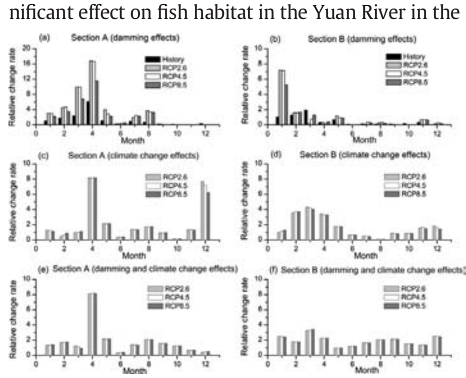
HIGHLIGHTS

- Increasing temperature, precipitation and runoff are expected in the future.
- Ecological habitat quality would be generally improved after cascade hydropower development.
- Diverse individual and cumulative effects are quantified for different river segments.
- Future uncertainties from inter-model, emission scenario and GCM bias are discussed and alleviated.

GRAPHICAL ABSTRACT

Monthly relative change rate of ecological conservation degree in the Yuan River Basin. (a) damming effects of Section A; (b) damming effects of Section B; (c) climate change effects of Section A; (d) climate change effects of Section B; (e) cumulative effects of Section A; (f) cumulative effects of Section B.
The construction of cascade dams have a more significant impacts on fish habitat quality from January to April for Section A and January to March and May for Section B, respectively. Climate changes have a significant effect on fish habitat quality in April and December for Section A, and it is generally lower than that under cascade development; whereas the climate change impacts on Section B is high in dry seasons but low in flood seasons, and the effect is particularly more pronounced than that of hydropower development. Under climate changes and cascade development, the distribution patterns and ranges of the relative change rates of the ecological conservation degrees of both Section A and Section B are close to that under climate changes. Climate changes have a more significant effect on fish habitat in the Yuan River in the future.



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ABSTRACT

The eco-hydrological system in southwestern China is undergoing great changes in recent decades owing to climate change and extensive cascading hydropower exploitation. With a growing recognition that multiple drivers often interact in complex and nonadditive ways, the purpose of this study is to predict the potential future changes in streamflow and fish habitat quality in the Yuan River and quantify the individual and cumulative effect of cascade damming and climate change. The bias corrected and spatial downscaled Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Model (GCM) projections are employed to drive the Soil and Water Assessment Tool (SWAT) hydrological model and to simulate and predict runoff responses under diverse

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scenarios. Physical habitat simulation model is established to quantify the relationship between river hydrology and fish habitat, and the relative change rate is used to assess the individual and combined effects of cascade damming and climate change. Mean annual temperature, precipitation and runoff in 2015–2100 show an increasing trend compared with that in 1951–2010, with a particularly pronounced difference between dry and wet years. The ecological habitat quality is improved under cascade hydropower development since that ecological requirement has been incorporated in the reservoir operation policy. As for middle reach, the runoff change from January to August is determined mainly by damming, and climate change influence becomes more pronounced in dry seasons from September to December. Cascade development has an effect on runoff of lower reach only in dry seasons due to the limited regulation capacity of reservoirs, and climate changes have an effect on runoff in wet seasons. Climate changes have a less significant effect on fish habitat quality in middle reach than damming, but a more significant effect in lower reach. In addition, the effect of climate changes on fish habitat quality in lower reach is high in dry seasons but low in flood seasons.

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1. Introduction

There have been increasing concerns in recent years over the ecological impacts of the extensive construction of cascade hydropower stations in southwestern China despite their high aquatic productivity and great hydropower potential (Fu et al., 2014; He et al., 2014). The Yuan River is a transboundary river flowing through the mountainous area in southwestern China, and it will be highly exploited for hydropower generation due to the increasing demand for energy in China. A total of eleven cascade dams will have been constructed on the Yuan River by 2030, which could dramatically alter the flow regime of the river. This region is located in the transition zone between East Asian, Indian, and Tibetan Plateau monsoons, and thus global warming could magnify the ecological risks that are already present through its potential to alter rainfall, temperature and stream flow patterns, and to disrupt biological communities and sever ecological linkages (Palmer et al., 2009; Tan, 2014). The rapid hydropower development and climate change in the Yuan River basin has raised concern among conservationists in recent years (Fu et al., 2014), but the effects and contributions of natural and anthropogenic forcing are still unclear and intensely debated (Kong et al., 2016; L.H. Wu et al., 2017).

The damming effect on the runoff and ecology has been widely discussed (L.H. Wu et al., 2017). A tentative conclusion is that the construction of cascade hydropower stations can profoundly alter the hydrological regime of rivers in southwestern China, resulting in low-to-moderate flow magnitudes (Kibler and Alipour, 2017). The water discharge in dry seasons of Lancang-Mekong River, the largest international river in southwestern China, was obviously lower in the post-dam period than in the pre-dam period, whereas that in wet seasons was marginally lower in the post-dam period (Lu et al., 2014; Rasanen et al., 2017). Fish is one of the most vulnerable species to flow regulation. Damming poses a major threat to fish habitat by changing its physical properties, including continuity, flow distribution, organic matter, water velocity, water depth and water temperature (Fan et al., 2015; Kang et al., 2009; Kibler and Tullos, 2013; Li et al., 2013; Yi et al., 2014). However, Zhai et al. (2010) argued that the ecosystem integrity of the Yuan River could be improved after river regulation. There has been much debate over this question and no clear conclusion has been reached on the damming effect on the Yuan River. Also, most previous studies have focused on a single dam rather than cascade reservoirs.

There has been a trend of climate warming and increased precipitation at both annual and seasonal scales in southwestern China since 1960s (Ma and Zhou, 2015; Tang et al., 2015; Miao et al., 2016a, 2016b). Future expected changes include aggravating drought and more intense climate extremes (Ma and Zhou, 2015; Wen et al., 2016a, 2016b; Zhai et al., 2010). However, the potential impact on the future runoff regime of rivers in southwestern China, such as the Lancang-Mekong River, will probably decrease in wet seasons and increase in dry seasons (Tang et al., 2015). Climate change has a profound effect on sediment trapping, water conservation and species conservation in southwestern China, causing slight degradation in the ecological systems in recent decades (Guo et al., 2016). Jiang and Zhang (2016) proposed the InVEST model to assess the habitat quality of rivers in southwestern China. Until now, few studies have focused on the impacts of climate change on fish habitats in southwestern China. General Circulation Model (GCM) projections have also been used in the assessment of future climate change impacts. However, the GCM outputs tend to be biased wet, dry, cool, and/or warm compared with observations (Ehret et al., 2012; Taylor et al., 2012), and thus the reliability of the conclusions might be undermined (Miao et al., 2016a, 2016b).

Another issue is how to identify and quantify the ecological requirements. The term of ecological flow regime (Poff et al., 1997) is commonly used to refer to the flow regime designed to continuously maintain a river under specific ecological conditions with some special hydrological characteristics such as flow magnitude, frequency, duration, change rate and time. Tharme (2003) reviewed the development and application of over 200 environmental flow methodologies for rivers, which could be grouped into four reasonably distinct categories, namely hydrological, hydraulic rating, habitat simulation (or rating), and holistic methodologies. The Physical Habitat Simulation Model (PHABSIM) is a classical habitat simulation technique proposed in the early 1970s and further refined and expanded into a library of models for hydraulic simulation and habitat analysis (Milhous et al., 1989). PHABSIM can provide a better understanding of how the hydraulic habitat of fish species changes in response to the alteration of the flow regime, and thus the optimal ecological discharge can be determined based on the habitat-flow curves (Wilding et al., 2014). For example, Gibbins et al. (2001) determined the ecologically acceptable river flow regimes of Kielder reservoir and water transfer system using PHABSIM. PHABSIM was also applied in ecological flow estimation for 63 sites in the UK (Booker and Acreman, 2007), Rivers Allen and Piddle dominated by groundwater flows in southern England (Elliott et al., 1999), Girnock Burn in Scotland (Gibbins et al., 2002), Gokasegawa River, Hourigawa River and Kitagawa River in Japan (Nagaya et al., 2008), and Cache la Poudre River in the USA (Williams, 2010). Li et al. (2015) introduced the landscape ecology method to integrate habitat quality into ecological flow estimation.

As for southwestern China, climate change and damming effects on ecohydrology are typically studied and managed independently, although there is a growing recognition that multiple drivers often interact in complex and nonadditive ways. The purpose of this study is to predict the potential future changes in stream flow and fish habitat quality in the Yuan River, and assess the individual and combined effect of cascade reservoir development and climate change. Specifically, the BCSD downscaled CMIP5 GCM projections are employed to drive the Soil and Water Assessment Tool (SWAT) hydrological model and to simulate and predict runoff responses under diverse scenarios. PHABSIM is established to quantify the relationship between river hydrology and fish habitat, and the relative change rate is used to assess

the individual and combined effect of cascade reservoir development and climate change.

2. Research area and data

2.1. Research area

2.1.1. Yuan River basin

The Yuan River is located in southwestern China (East: 100.01°–105.67°, North: 22.45°–25.53°), with a total length of 692 km and a drainage area of 34,629 km^2. Its two main tributaries, the Lishe River and the Shiyang River which originate from the Weishan City of Yunnan Province, join at the Sanjiangkou to form the Yuan River (Fig. 1). Then, it flows through the southwestern China and Vietnam before emptying into the sea. There are some large branches flowing into the main reach of the Yuan River, including Tengtiao River, Nanxi River, and Panlong River.

Locating in the subtropical monsoon climate zone, the average annual temperature of the basin is between 14.7 °C and 23.8 °C, and the temperature differences in four seasons are not quite significant. The average annual rainfall of the basin is 1347 mm, indicating the decreasing trend from northwest to southeast over the entire basin. The wet and dry seasons are quite evident here, the flood season (June to November) accounts for 76% to 88% of the annual runoff, while the dry season (from December to next May) only occupies 12% to 24%.

2.1.2. Cascade reservoirs

Principal flow regulation capabilities within the basin are restricted to the main reach of Yuan River from Sanjiangkou (the location of Jiasajiang Reservoir) to Hekou (China-Vietnam border), while most of its branches and the upper basin are essentially unregulated. In 2011, the construction of eleven cascade reservoirs on the Yuan River was officially approved. Currently, Nansha Reservoir and Madushan Reservoir have been put into operation for stream regulation, while Jiasajiang Reservoir, Qiaotou Reservoir and Daheigong Reservoir have been under construction. The other six reservoirs are daily-regulated run-of-river hydropower stations, all of which are still in the planning or designing process. These six cascade reservoirs will not significantly change the flow regime on a 10-day basis (the time step used in this study). Here, we focus on the impacts of the five cascade reservoirs constructed or under construction, namely Jiasajiang Reservoir, Qiaotou Reservoir, Daheigong Reservoir, Nansha Reservoir and Madushan Reservoir. The basic parameters and locations of these reservoirs are shown in Table 1 and Fig. 1, respectively.

2.2. Research data

2.2.1. Observed and GCM projected climate data

The historical climate data are used to calibrate the hydrological model of Yuan River Basin and to downscale the GCM outputs to a finer resolution. Here, the daily precipitation and the maximum and minimum air temperature during 1961–2010 are obtained from the six meteorological stations of China Metrological Data Sharing Service, including Chuxiong (ID No. 56768), Jingdong (ID No. 56856), Yuxi (ID No. 56875), Yuanjiang (ID No. 56966), Mengzi (ID No. 56985) and Pinbian (ID No. 56968), as shown in Fig. 1. Twenty CMIP5 GCMs are used to alleviate the inter-model uncertainties. A total of 43, 50 and 45 ensemble members were respectively used in RCPs 2.6, 4.5 and 8.5, the multi-ensemble means are used as the corresponding GCM outputs. Table 2 shows these models and their atmospheric component resolution and institutions. Daily temperature and precipitation modeling projections

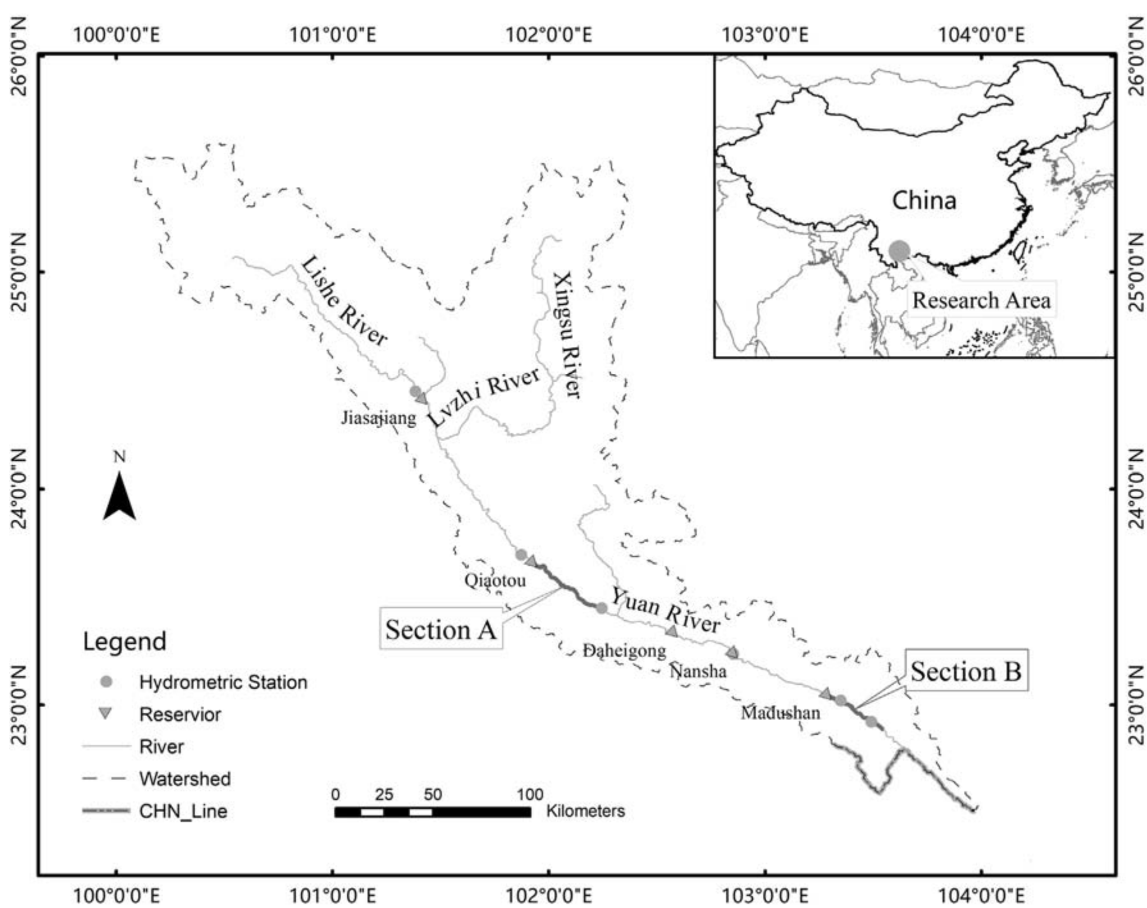

Fig. 1. The geographic location and river networks of Jiasajiang and Madushan reservoir.

Table 1
The basic properties of the five cascade reservoirs on the Yuan River.

Properties	Unit	Jiasajiang reservoir	Qiaotou reservoir	Daheigong reservoir	Nansha reservoir	Madushan reservoir
Basin area	km^2	18,102	21,253	28,376	28,875	31,356
Regulation ability	–	Annual	Seasonal	Seasonal	Seasonal	Seasonal
Mean annual flow	m^3/s	133	165	258	261	302
Available storage	10^8 m^3	14.91	2.84	4.03	2.88	4.82
Normal water level	m	675	450	340	267	217
Dead water level	m	640	440	320	255	199
Maximum turbine release	m^3/s	270	275	441.5	386	490
Output efficiency	–	8.6	8.6	8.6	8.8	8.8

during 2015–2100 can be obtained from http://cmip-pcmdi.llnl.gov/. Three Representative Concentration Pathways (RCP) scenarios are selected, namely RCP2.6, RCP4.5 and RCP8.5, which are defined and named according to their total radiative forcing in 2100 relative to pre-industrial values (+2.6, +4.5 and + 8.5 W/m^2, respectively), representing the low, medium and high emission conditions, respectively.

2.2.2. Runoff and fish habitat data

Both observed hydrological data and the behavior data of aquatic species of the Yuan River are used in this study. Specifically, the runoff data are collected at the gauging stations (Fig. 1) on a daily basis from Jan. 1979 to Dec. 2010. The behavior data of aquatic species are provided by the Fishery Bureau of Yunnan Province, including the life stages of target fish species (*Cyprinus rubrofuscus* Lacépède and *Bagarius rutilus* Ng et Kottelat, referred to as *B. rutilus*), and their preference for flow velocity and water depth at each life stage. The habitat of *Cyprinus rubrofuscus* Lacépède and *B. rutilus* in the Yuan River was simulated using these data in our previous study (Wen et al., 2016a).

2.2.3. Geospatial data

Some other data are required to simulate the hydrological process using SWAT model, including Digital Elevation Model (DEM), land use/cover data and soil map. Specifically, NASA Shuttle Radar Topography Mission (SRTM) DEM (90 m) is used to generate the boundary and stream network of the basin. The land-use data are extracted from China Soil Map Based Harmonized World Soil Database V1.1 (1:1,000,000 resolution) which is provided by the Food and Agriculture Organization of the United Nations and International Institute for Applied Systems Analysis. In addition, the land-use and soil data are reclassified according to the input requirement of the SWAT model and China soil classification system.

3. Methods

3.1. BCSD downscaling

The comparison of historical simulation results from GCMs with observations often shows that the simulations tend to be biased wet, dry, cool, and/or warm, and the bias varies with location, season and variable. To address this problem, Bias Correction and Spatial Disaggregation (BCSD) method, a statistical downscaling technique developed by Wood et al. (2002), is performed to establish empirical relationships between GCM-resolution climate variables and local climate and to reproduce regional climate features. It offers a more immediate solution and significantly lower computing requirements, and could be easily transferred to other regions.

The classical BCSD method is proposed for monthly temperature and precipitation downscaling. However, this method could also be performed on a daily time step. Generally, it mainly involves the following two steps: (1) Bias Correction. A quantile mapping of daily temperature and precipitation from GCMs to observations regridded to the coarse model resolution is employed to identify and remove the bias. Specifically, a bias-corrected value for a GCM-simulated daily value is retrieved by using the CDF for the GCM to determine the quantile associated with the value, and then drawing the observed value from that same day's

Table 2
WCRP-CMIP5 models used in the study.

Name	Atmospheric resolution (lon × lat)	Institution	Ensembles		
			RCP 2.6 runs	RCP 4.5 runs	RCP 8.5 runs
bcc-csm1-1	~2.8° × 2.8°	Beijing Climate Center, China Meteorological Administration	1	1	1
Bnu-esm	~2.8° × 2.8°	Beijing Normal University	1	1	1
CanESM2	~2.8° × 2.8°	Canadian Centre for Climate modeling and Analysis	1–5	1–5	1–5
CCSM4	1.25° × 0.9°	National Center for Atmospheric Research	1–5	1–5	1–5
CESM1-CAM5	1.25° × 0.9°	National Center for Atmospheric Research	1–3	1–3	1–3
CNRM-CM5	~1.4° × 1.4°	Centre National de Recherches Meteorologiques, Meteo-France		1	
CSIRO-Mk3.6.0	1.875° × 1.875°	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence	1–5	1–5	1–5
Ec-earth	0.7° × 0.7°	EC-EARTH Consortium	8,12	2,8,12	6,8,12
FGOALS-G2	~4.7° × 2.8°	Institute of Atmospheric Physics, Chinese Academy of Sciences; and CESS, Tsinghua University	1	1	1
FIO-ESM	~2.8° × 2.8°	The First Institute of Oceanography, SOA	1–3	1–3	1–3
Gfdl-esm2g	2.5° × 2°	Geophysical Fluid Dynamics Laboratory	1	1	1
GISS-E2-R	2.5° × 2°	NASA Goddard Institute for Space Studies	1	1–5	1
HadCM3	2.5° × 3.5°	Met Office Hadley Centre	1	1	1
Hadgm2-es	~1.875° × 1.2°	Met Office Hadley Centre	1–4	1–4	1–4
INMCM4	1.5° × 2°	Institute for Numerical Mathematics	1	1	1
IPSL-CM5A-LR	3.75° × 1.875°	Institute Pierre-Simon Laplace	1–3	1–4	1–4
MIROC5	~1.4° × 1.4°	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	1	1	1
MPI-ESM-LR	1.875° × 1.875°	Max-Planck-Institut für Meteorologie	1–3	1–3	1–3
MRI-CGCM3	1.125° × 1.125°	Meteorological Research Institute	1	1	1
NorESM1-M	2.5° × 1.875°	Norwegian Climate Centre	1	1	1

CDF for the same quantile. Bias Correction matches the statistical moments of observations and GCM output covering a common time period (e.g. 20th century), and accordingly adjusts for biases in GCM output for projected time periods (e.g. 21st century). (2) Spatial Disaggregation. The bias-corrected precipitation and temperature are spatially disaggregated to the fine-resolution grid by SYMAP interpolating and then applying fine-resolution spatial anomaly patterns derived from the observations. The anomalies are calculated as the correction factors (for precipitation) and summands (for temperature) between the fine-resolution observations and the coarsened observations interpolated to the fine-resolution grid (Wood et al., 2004).

The gaged-based observations are converted to the grid-based data and are used as the historical records to remove the bias in CMIP5 GCM projections. All future precipitation and temperature projections are downscaled to the grid scale (0.5° × 0.5°) on a daily basis.

3.2. SWAT hydrological simulation

The SWAT is selected to simulate stream flow. It is a physically-based, semi-distributed and continuous time step ecohydrological model (Arnold et al., 1998). The hydrological processes, a main component of the SWAT model, consist of surface runoff, evapotranspiration, percolation, infiltration, aquifer flow (shallow and deep), and channel routing (Arnold and Allen, 1996). The catchment is initially divided into several subbasins and then further divided into a number of Hydrological Response Units (HRUs) with homogeneous soil type and land use. On the basis of water balance, each HRU operates in five phases: (1) precipitation interception, (2) surface runoff, (3) soil and root zone infiltration, (4) evapotranspiration and soil and snow evaporation, and (5) groundwater flow (Babar and Ramesh, 2015). See Arnold et al. (1998) for details.

The performance of model simulation is evaluated by Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (R^2), as shown in Eqs. (1) and (2). In particular, the simulation results are considered acceptable if $NSE > 0.5$ mean or $R^2 > 0.5$.

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(Q_{o,i} - Q_{m,i}\right)^2}{\sum_{i=1}^{n} \left(Q_{o,i} - \overline{\overline{Q}}_o\right)^2} \tag{1}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)\left(Q_{s,i} - \overline{Q}_s\right)\right]^2}{\sum_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)^2 \sum_{i=1}^{n} \left(Q_{s,i} - \overline{Q}_s\right)^2} \tag{2}$$

where $Q_{o,\,i}$, $Q_{m,\,i}$ are the ith observed and simulated data, $\overline{Q}_o$, $\overline{Q}_s$ are the mean observed and simulated data, and n is the total number of observations, respectively.

3.3. Physical habitat simulation model

PHABSIM is proposed to simulate the relationship between the stream flow and the physical habitat for various life stages of fish species, and then to determine the optimal ecological flow for a given river reach. The classical PHABSIM consists of hydraulic simulation and habitat modeling. In the hydraulic simulation module, the MANSQ model (Manning's equation) is used to calibrate and simulate the stage-discharge relationship of each cross-section, based on which a one-dimensional hydraulic simulation model is proposed to determine characteristics of the stream in terms of depth and velocity as a function of the discharge. For habitat modeling, the river sectors and aquatic species most vulnerable to the variation of stream flow should be identified initially (Maddock et al., 2001). Then, the Habitat Suitability Index (HSI) is introduced to describe the preference of target fish species for flow velocity, depth, and channel properties (Booker and Acreman, 2007). Basically, HSI can be determined according to the number of fish population at the target point. The maximum HSI value is set to 1.0, and the other HSI values are determined in terms of relative ratio to the maximum value (Williams, 2010). In this study, HSIs associated with water depth and flow velocity are calculated based on the physical measurement and intensive fieldwork involving identifying, measuring and mapping the species' habitat characteristics (Li and Xia, 2011) by the Fishery Bureau of Yunnan Province, and proposed in the format of Habitat Suitability Curve (HSC), which is an univariate curve representing the trend of HSI that quantify habitat suitability for fish survival as a function of hydraulic variables.

The Weighted Usable Areas (WUA) (Bovee, 1986) is used to reflect the amount of physical habitat available for fish species under different flow conditions (Lee et al., 2010), which can be calculated as an aggregate of the product of a composite HSI in Eq. (3).

$$WUA_i = (v_i \times d_i \times S_i)A_i \tag{3}$$

where WUA_i is the WUA at cross-sectional segment i, v_i is the species-life stage HSI value for velocity at cross-sectional segment i, d_i is species-life stage HSI value for depth at cross-sectional segment i, S_i is species-life stage HSI value for substrate type at cross-sectional segment i, A_i is area of cross-sectional segment i.

The ideal situation in which the optimal ecological flow is released can be hardly achieved in practical operation of cascade reservoirs. The optimal ecological flow rate can be estimated via flow versus WUA relations, corresponding to the vertex with the largest WUA value (Olsen et al., 2014; Petts and Maddock, 1994). Here, the conservation degree is determined as the ratio of the current WUA value to the maximum WUA projected by the WUA-flow rate relationship. A schematic of this procedure with a 70% conservation degree is shown in Fig. 2.

3.4. Scenarios

One actual and three hypothetical scenarios are proposed to assess the cumulative and individual contribution of cascade development and climate change. Scenario 1 (baseline) represents the historical natural unregulated state, Scenario 3 evaluates the future natural condition without dam regulation. Scenarios 2 and 4 assume the regulated conditions for historical and future, respectively.

3.5. Relative change analysis

The relative change rate is an indicator that quantifies the effect of a possible influence factor on the outcome variable. It is defined as the ratio of the difference in the outcome variable before and after the onset of the influence factor to the standard deviation, where the

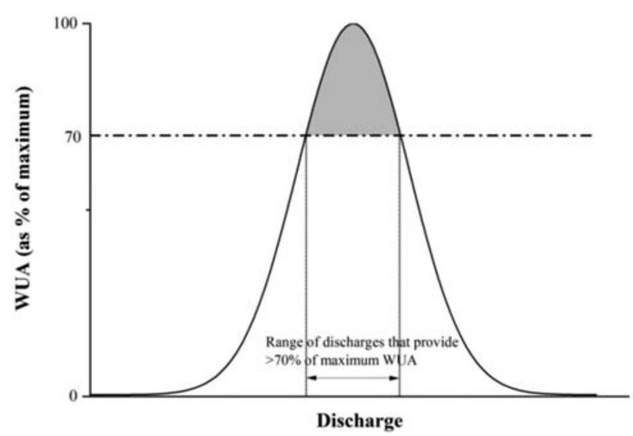

Fig. 2. A schematic of the determination of ecological requirements (Wen et al., 2016a, 2016b).

difference is used to characterize the change of outcome variable attributed to the influence factor, whereas the standard deviation is used to characterize the discrete distribution of the outcome variable under natural conditions. The relative change rate makes it possible to compare the relative contribution of influence factor and natural tendency, which thus provides a better understanding of the effect of the influence factor.

In this study, we analyzed the individual and joint contribution of cascade development and climate change to runoff and fish habitat in the Yuan River basin. The relative change rate of runoff attributed to cascade development α_1 is defined as the ratio of the difference in runoff before and after cascade development to the standard deviation of natural runoff. The relative change rate of runoff attributed to climate change α_2 is defined as the ratio of the change in runoff under no cascade development in 2015–2100 relative to that in 1951–2010 to the standard deviation of natural runoff in 1951–2010. The relative change rate of runoff attributed to cascade development and climate change α_3 is defined as the ratio of the change in runoff under cascade development in 2015–2100 relative to that in 1951–2010 to the standard deviation of natural runoff in 1951–2010. Under no cascade development, the relative change rate of habitat quality attributed to cascade development α_4 is defined as the ratio of change in ecological conservation degree before and after the operation of cascade reservoirs to the standard deviation under natural conditions. The relative change rate of habitat quality attributed to cascade development and climate changes α_5 is defined as the ratio of change in ecological conservation degree in 2015–2100 relative to that in 1951–2010 under no cascade development to the standard deviation under natural conditions. The relative change rate of habitat quality attributed to cascade development and climate changes α_6 is defined as the ratio of change in ecological conservation degree in 2015–2100 relative to that in 1951–2010 under cascade development to the standard deviation under natural conditions.

$$\alpha_{i,j} = \left|\frac{d_j}{D_j}\right|, i = 1, 2, \ldots, 6; \mathrm{j} = 1, 2, 3, \ldots, 12 \tag{4}$$

$$D_j = \sqrt{\sum_{m=1}^{n} \left(X_{jm} - \overline{X_j}\right)^2}, \mathrm{j} = 1, 2, 3, \ldots, 12 \tag{5}$$

$$d_j = \overline{X_j} - \overline{x_j}, j = 1, 2, 3, \ldots, 12 \tag{6}$$

where α_{ij} is the elative variation rate of mean monthly runoff or ecological conservation degree of the jth month; D_j is the standard deviation of

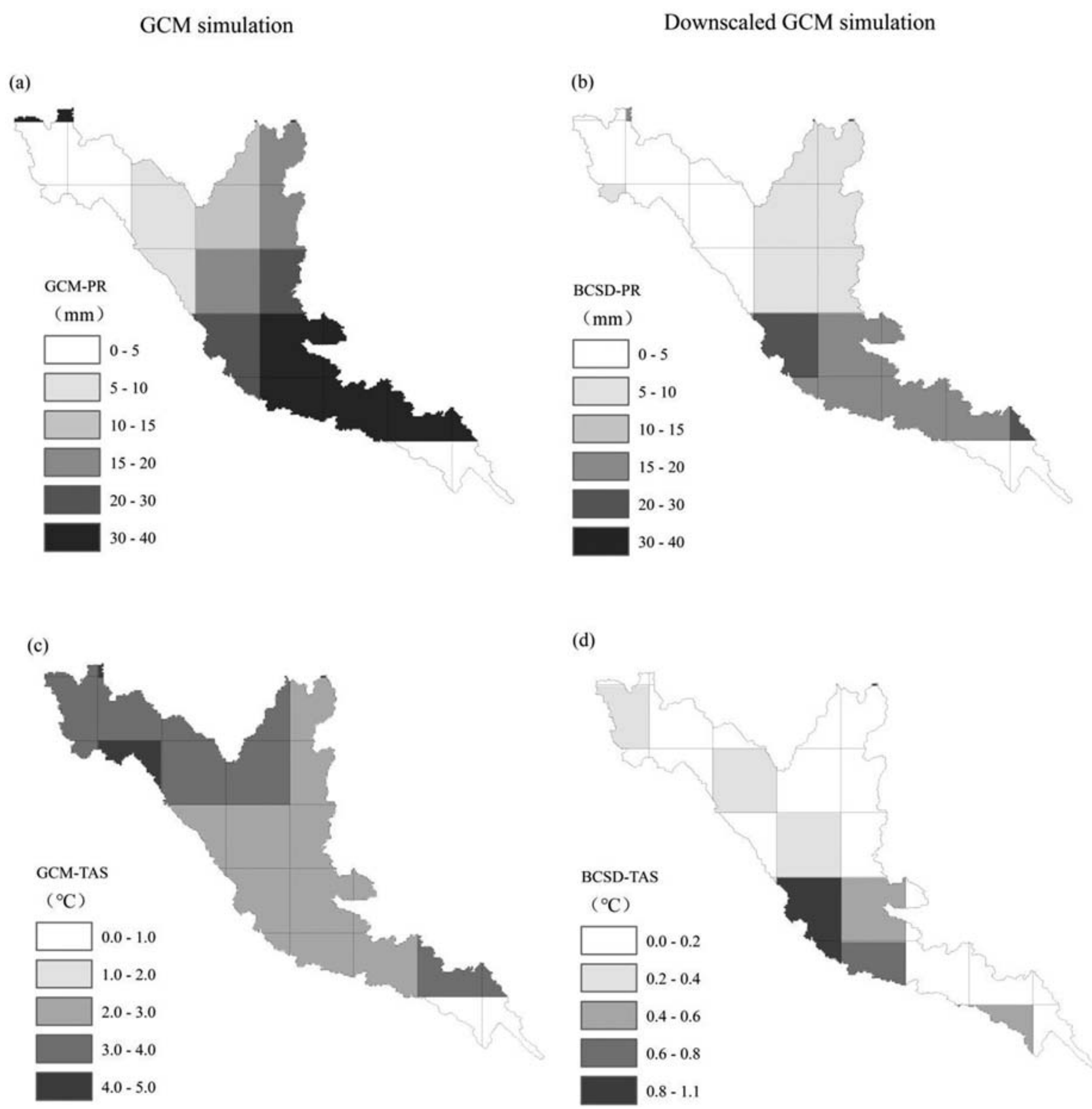

Fig. 3. The spatial distribution of the bias of historical CMIP5 and BCSD downscaled multi-model mean precipitation (a, b) and temperature (c, d) in the Yuan River basin.

mean runoff or the ecological conservation degree of the jth month; d_j is the difference in the mean annual flow rate or ecological conservation degree of the jth month under the influence of cascade development or climate changes; X_{jm} and $\overline{X_j}$ are the mean monthly or annual runoff or ecological conservation degree in different years before the influence of cascade development or climate changes; n is the number of research years; and $\overline{x_j}$ is the mean annual runoff and ecological conservation degree after the influence of cascade development or climate changes, respectively.

4. Results

4.1. Assessment of temperature and precipitation changes

4.1.1. Performance of BCSD downscaling

The future projections of temperature and precipitation were bias corrected and spatially downscaled by using the BCSD method, and the downscaling performance was evaluated by comparing downscaled historical GCM simulations with observations from January 1950 to December 2010. To calculate the bias, we converted GCM simulations and observed data into grid scale with the same spatial resolution $0.5^\circ * 0.5^\circ$. Fig. 3 shows the spatial distribution of the bias of historical CMIP5 and BCSD downscaled multi-model mean precipitation and temperature in the Yuan River basin. It is clearly evident that BCSD downscaling can significantly improve GCM temperature and precipitation output. Specifically, the bias of GCM precipitation ranges from 10 to 40 mm, whereas that of BCSD downscaled GCM precipitation ranges from 5 to 20 mm. More importantly, the bias of GCM temperature ranges from 1 to 4 °C and reaches up to 5 °C in some norther areas, whereas that of BCSD downscaled GCM temperature is reduced to 0–0.6 °C.

4.1.2. Future changes in temperature

Fig. 4 shows the time series of downscaled CMIP5 multi-model annual mean temperature averaged over Yuan River Basin in 2015–2100. The mean annual temperature of Yuan River Basin in 1951–2010 is 16.92 °C; while that in 2015–2100 is increased dramatically by 1.31–2.60 °C at a rate of 0.080–0.495 °C/10a relative to that in 1951–2010. The mean annual temperature is sensitive to radiation intensity, and it increases significantly with increasing radiation intensity. The Yuan River basin has four distinctive seasons with a high mean monthly temperature of 20.8 °C from May to September. The mean monthly temperature under RCP2.6, RCP4.5 and RCP8.5 is increased by 1–4 °C relative to that in 1951–2010. The mean monthly temperature is low from October to April of the next year, with a minimum of 10–12 °C.

4.1.3. Future changes in precipitation

The Yuan River basin has a subtropical monsoon climate, and the precipitation in this basin is largely affected by monsoon circulation and southeast wind. As presented in Fig. 5, the mean annual precipitation in 1951–2010 is 1100.87 mm; while that in 2015–2100 is increased by 2.53–4.74% at a rate of 5.47–19.80 mm/10a relative to that in 1951–2010. In addition, precipitation is sensitive to radiative forcing, and it increases significantly with the increase of radiation intensity.

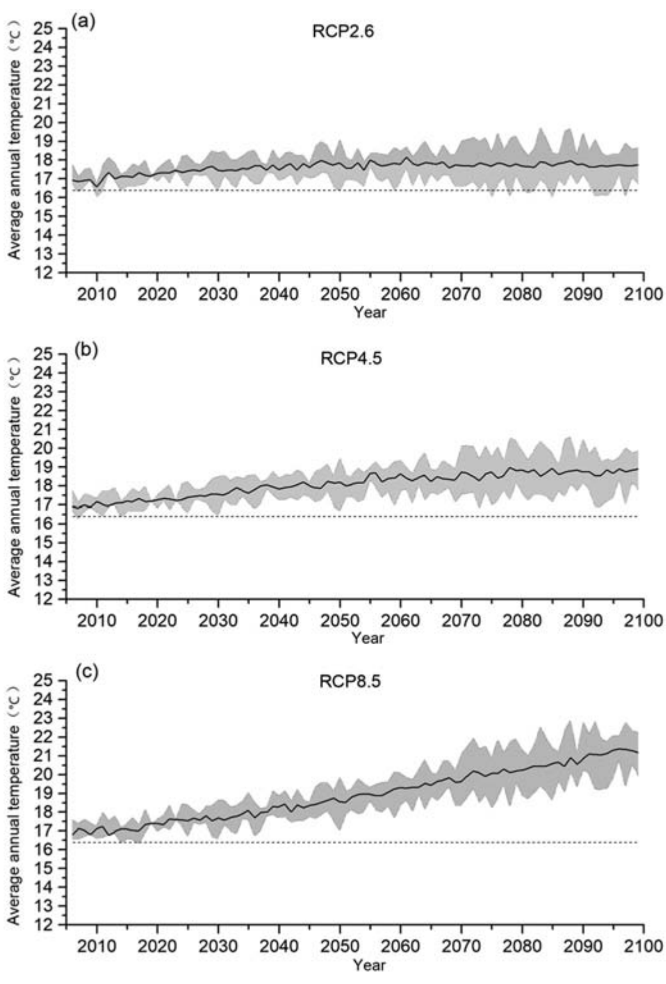

Fig. 4. Time series of annual mean temperature averaged over Yuan River Basin projected by downscaled CMIP5 GCMs in 2015–2100 under (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5, respectively. The solid lines indicate multi-model ensemble means, the dotted line is the annual mean temperature of the basin in 1961–2010. Shading area indicates the multi-model ensemble range at 90% confidence level.

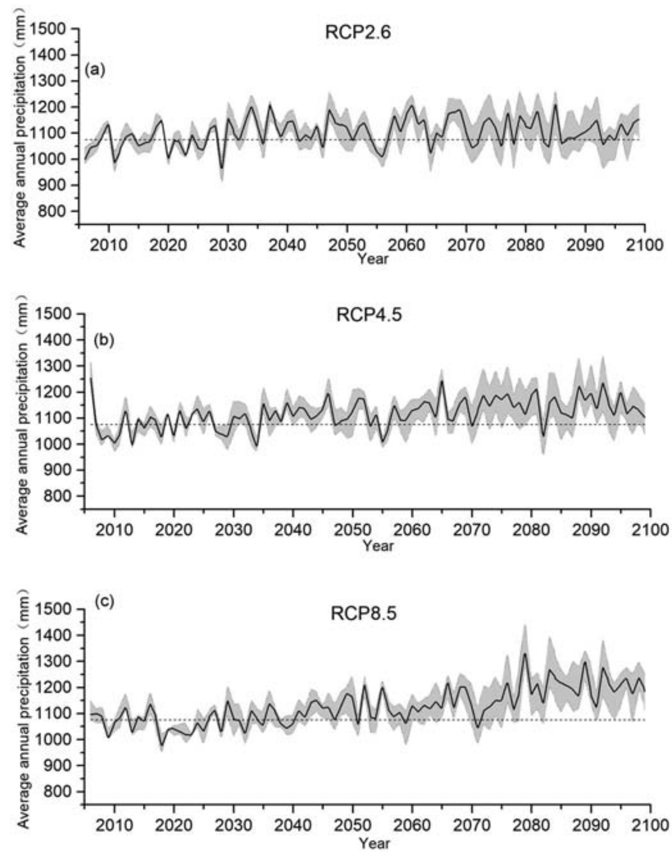

Fig. 5. Time series of annual precipitation averaged over Yuan River Basin projected by downscaled CMIP5 GCMs in 2015–2100 under (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5, respectively. The solid lines indicate multi-model ensemble means, the dotted line is the multi-year average precipitation of the basin in 1961–2010. Shading area indicates the multi-model ensemble range at 90% confidence level.

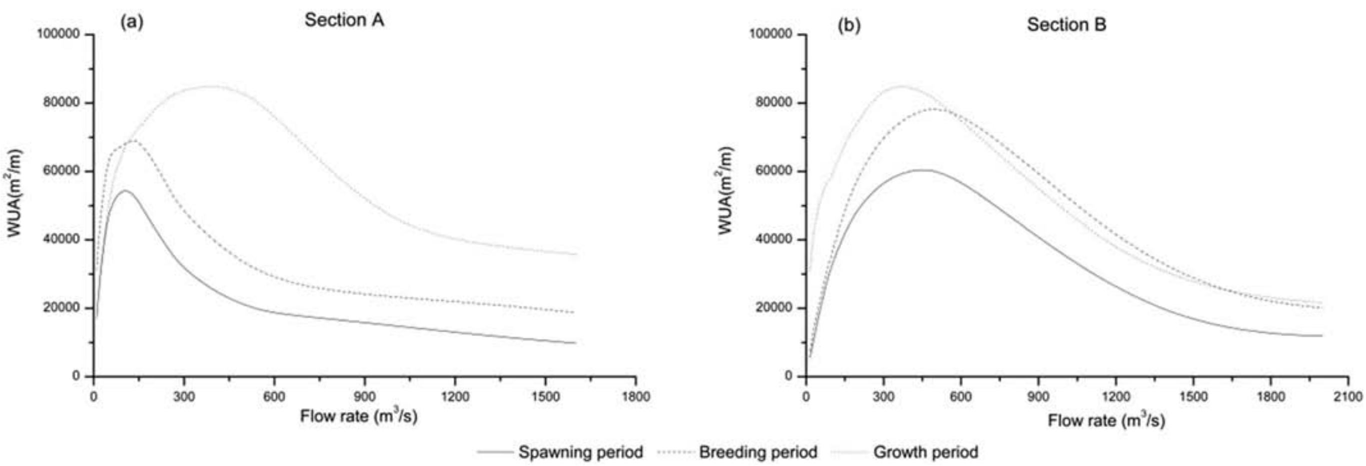

Fig. 6. The relationship between WUA and flow rate for different life stages of (a) *Cyprinus rubrofuscus* Lacépède in Section A and (b) *B. rutilus* in Section B.

There is a non-uniform distribution of mean monthly precipitations in the Yuan River basin, the precipitation from July to August accounts for 38.2% of the total precipitation in a year. As expected, the precipitation is low in dry seasons from November to April of the next year, accounts for 12.72% of the total precipitation in a year. In 2015–2100, no significant changes are observed in drought and flood periods. There is abundant precipitation from May to October, and that from July to August accounts for 40.1–41.6% of the total precipitation, with an increase of 1.9–3.4% relative to the same period in 1951–2005. The precipitation in dry seasons from November to April of the next year accounts for only 11–13.3% of the total precipitation.

4.2. Hydrological and fish habitat simulation

4.2.1. Fish habitat simulation

PHABSIM is developed to describe the changes in physical microhabitat in response to alterations in flow regime. In our previous research (Wen et al., 2016a), *Cyprinus rubrofuscus* Lacépède and *B. rutilus* are chosen as the target fish species due to their genetic diversity and great economic values. The Qiaotou-Luozhi section and Madu-Xinjie section of the Yuan River are identified as representative habitat of *Cyprinus rubrofuscus* Lacépède and *B. rutilus*, which are termed Section A and Section B in this study, respectively (Fig. 1). The detailed modeling process is seen from (Wen et al. (2016a)). Fig. 6 shows the WUA-flow rate relationships for different life stages of *Cyprinus rubrofuscus* Lacépède in Section A and *B. rutilus* in Section B, respectively. It is noted that all curves have an inverted “U” shape with a sharp rise and then a slow drop.

4.2.2. Hydrological simulation results

The SWAT model was calibrated on a monthly scale in 1981–2000 and validated in 2001–2010. Although the reservoirs do not exist before 2010, the runoff of river sections divided by these five reservoirs is simulated respectively, and then the runoff was accumulated at Section A

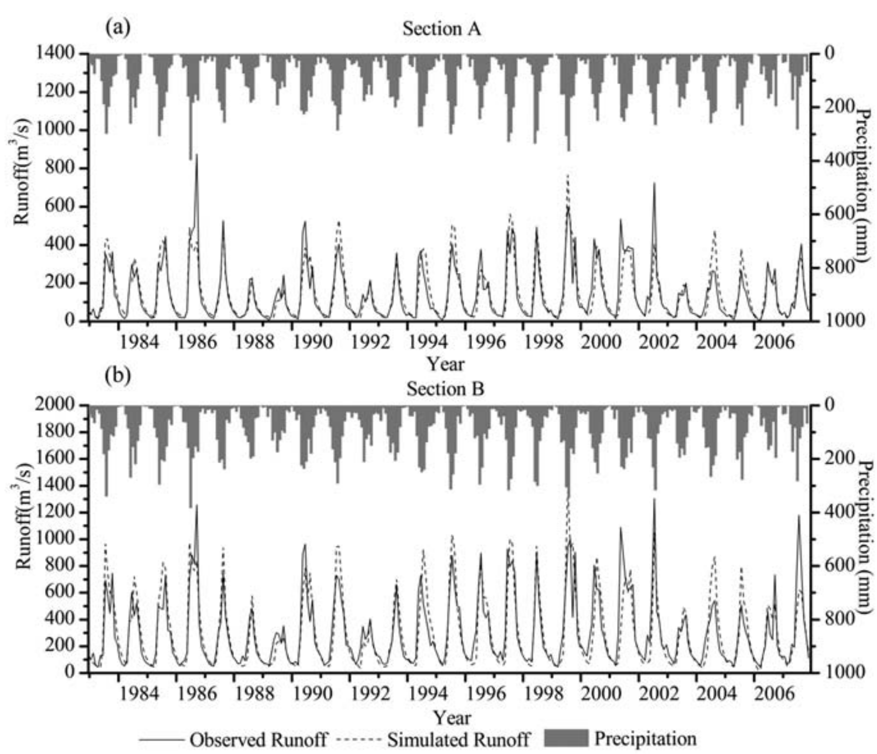

Fig. 7. The time series of simulated and observed inflow of (a) Section A and (b) Section B during 1981–2010.

Table 3
The performance of the SWAT model in hydrological simulation.

Basin	With seasonal cycle				Without seasonal cycle			
	Calibration		Validation		Calibration		Validation	
	R^2	*NSE*	R^2	*NSE*	R^2	*NSE*	R^2	*NSE*
Section A	0.83	0.83	0.78	0.77	0.71	0.69	0.64	0.63
Section B	0.84	0.83	0.75	0.75	0.68	0.68	0.69	0.64

and Section B. The modeling performance was evaluated by comparing SWAT simulated stream flow against the observed inflow of Section A and Section B. As shown in Fig. 7 and Table 3, there is a significant relationship between observed and simulated runoff with $R^2 > 0.75$ and $NSE > 0.75$. After removing the seasonal cycle, R^2 and *NSE* indicate a slight decrease, but are still larger than 0.60 for both Sections A and B. The simulated and observed mean monthly flow rate are 143.06 and 143.66 m^3/s for Section A, and 295.16 and 296.44 m^3/s for Section B, respectively.

4.3. Prediction of runoff and fish habitat quality

4.3.1. Hydrological prediction

The downscaled climate projections of each of the 20 CMIP5 GCMs were used to drive the calibrated SWAT hydrological model to predict

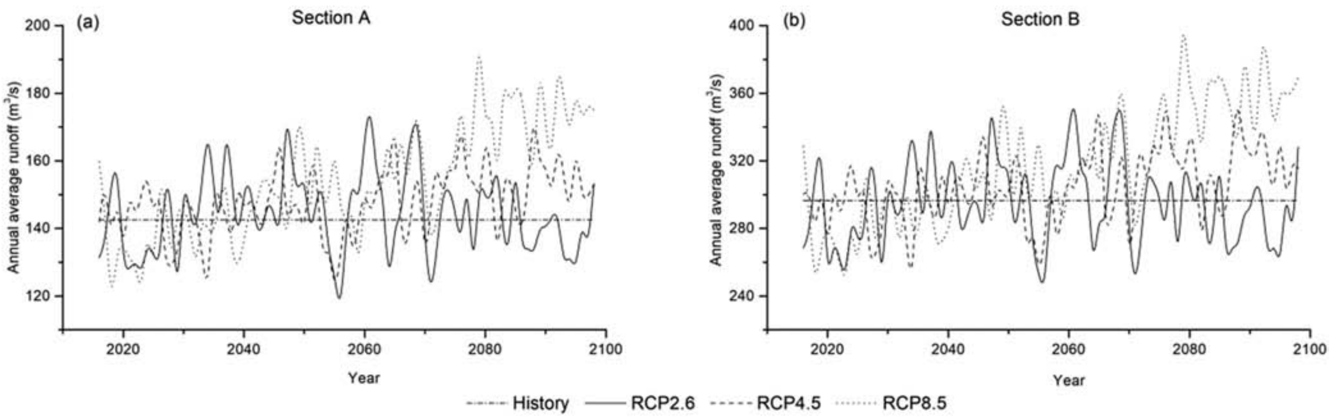

Fig. 8. Time series of predicted mean annual inflow (m^3/s) of (a) Section A and (b) Section B under unregulated conditions in 2015–2100 under RCP2.6, RCP4.5 and RCP8.5 respectively.

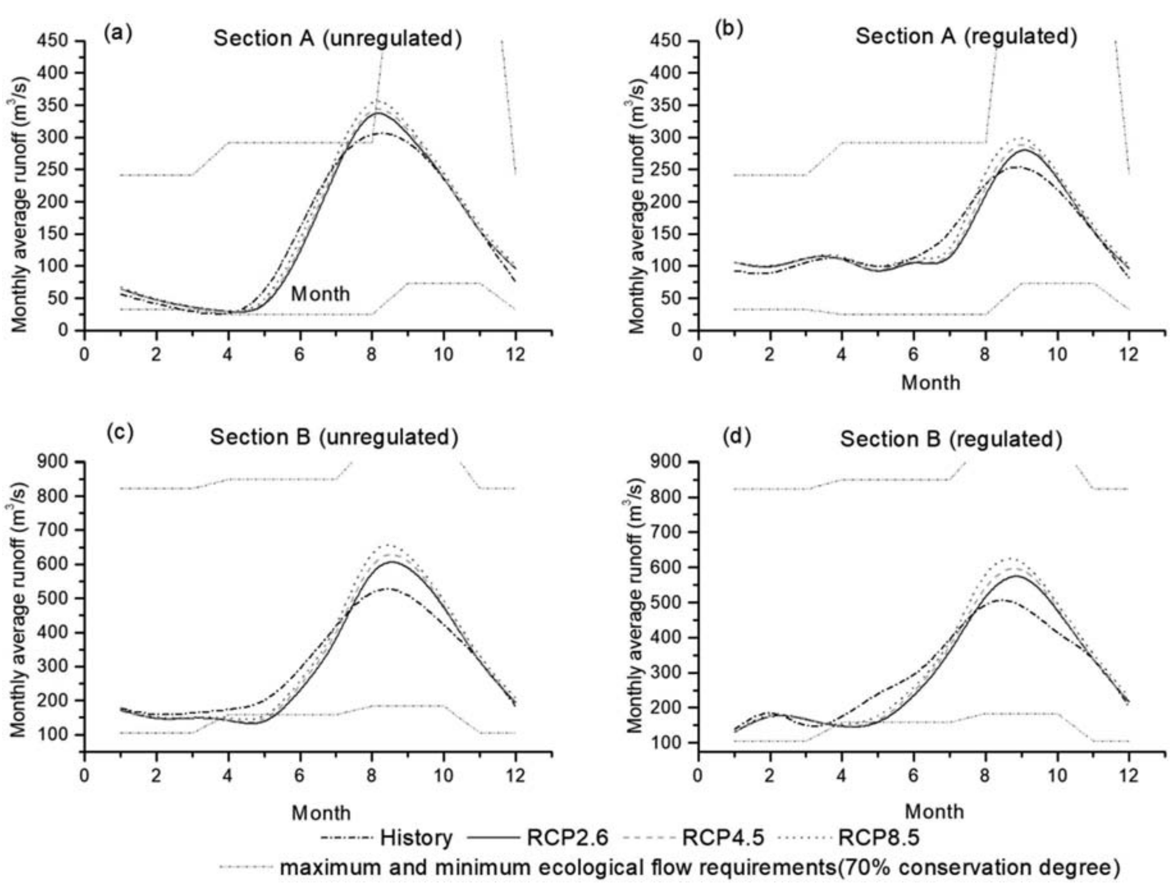

Fig. 9. The mean monthly runoff (m^3/s) in the Yuan River basin before and after cascade dam construction in 2015–2100 under RCPs 2.6, 4.5 and 8.5, respectively. The dash dotted lines indicate the monthly ecological flow limits at a 70% conservation degree. (a) Unregulated condition of Section A; (b) regulated condition of Section A; (c) unregulated condition of Section B; (d) regulated condition of Section B.

runoff in response to climate changes in the Yuan River Basin in 2015–2100. The natural inflow of the five reservoirs was simulated respectively, and then the reservoir discharge was simulated following the operation policy. Finally, the hydrological predictions were averaged to produce the time series of CMIP5 multi-model mean.

The Yuan River is recharged mainly by precipitation and partially by groundwater. Because Jiasajiang reservoir is an annual regulation reservoir, Qiaotou, Daheigong, Nansha and Madushan reservoirs are seasonal regulation reservoirs, the runoff on a yearly scale is less affected by cascade development. Thus, we investigated changes in runoff in Section A and Section B only under the conditions of no cascade development. Fig. 8 shows that in 1951–2010, the mean annual runoff is 142.49 m^3/s in Section A and 296.45 m^3/s in Section B, respectively; whereas that in 2015–2100 shows an increasing trend, but with a frequent alteration between dry and flood years. The mean annual runoff is 143.47–152.43 m^3/s in Section A and 293.36–313.33 m^3/s in Section B, with a variation of 0.69–6.98% and −0.96–5.69% in relative to that in 1951–2010, respectively. The runoff is sensitive to radiation intensity, and it increases with increasing radiation intensity. Under RCP2.6, the mean annual runoff remains largely stable, and the annual runoff is basically the same as the historical mean level. However, the annual runoff in Section B is slightly (−0.96%) lower than the historical mean level. Under RCP4.5 condition, future drought is projected to occur in 2030–2035 and 2050–2055 in Section B. Under RCP8.5, the mean annual runoff is increased significantly at a rate of 4.71 and 10.07 m^3/s per decade in Section A and Section B, respectively.

Fig. 9 shows that there is an uneven distribution of mean monthly runoffs in the Yuan River in 1951–2010. In the flood period from June to November, the natural runoffs of Section A and Section B account for 35.91% and 29.86% of the total runoff before reservoir regulation, and for 29.40% and 28.72% after reservoir regulation, respectively. In 2015–2100, the difference in natural runoff between dry and wet years would be further increased, resulting in high and concentrated runoff in flood seasons, and low but uniformly distributed runoff in non-flood seasons. Under no regulated conditions, the natural runoff of Section A and Section B is 237.84–252.93 m^3/s and 433.77–466.78 m^3/s with a CV value of 0.81 and 0.59 in flood seasons, with an increase of 0.83–5.46% and 3.2–11.15% relative to that in 1951–2010, respectively. In the major flood seasons from August to September, the mean runoff is increased by 8.94–14.54% and 15.49–25.11% relative to that in 1951–2010; and the total runoff in this period accounts for 82.89–84.17% and 73.93–74.50% of the total runoff, with an increase of 1.27–0.01% and 3.1–3.67%, respectively. In non-flood seasons, the natural runoff is 49.10–51.94 m^3/s and 152.9–159.76 m^3/s in Section A and Section B, with a decrease of −4.3–8.84% and 7.6–11.55% relative to that in 1951–2010; while the total runoff in this period is also decreased by 4.89–4.98% and 6.98–7.55%, respectively.

Cascade development contributes to reduce the difference in monthly runoff between dry and wet periods in a year, as shown in Fig. 9, The CV values of Section A and Section B are 0.49 and 0.56, respectively. The mean runoff of Section A, which is mainly regulated by Jiasajiang reservoir (an annual regulation reservoir) and Qiaotou reservoir (a seasonal regulation reservoir), is 185.74–200.73 m^3/s in future flood seasons under cascade development, with a decrease of 20.6–21.9% compared with future natural runoff. The runoff in flood seasons account for 64.73–66.32%, with a decrease of 17.09–18.15% compared with that under no cascade development. The mean runoff of Section B, which is mainly regulated by three seasonal regulation reservoirs and less affected by cascade development, is 185.74–200.73 m^3/s in future flood seasons under cascade development, with a decrease of 2.6–2.7% compared with future natural runoff. The runoff in flood seasons account for 64.73–66.32%, with a decrease of 1.95–2.01% compared with that under no cascade development.

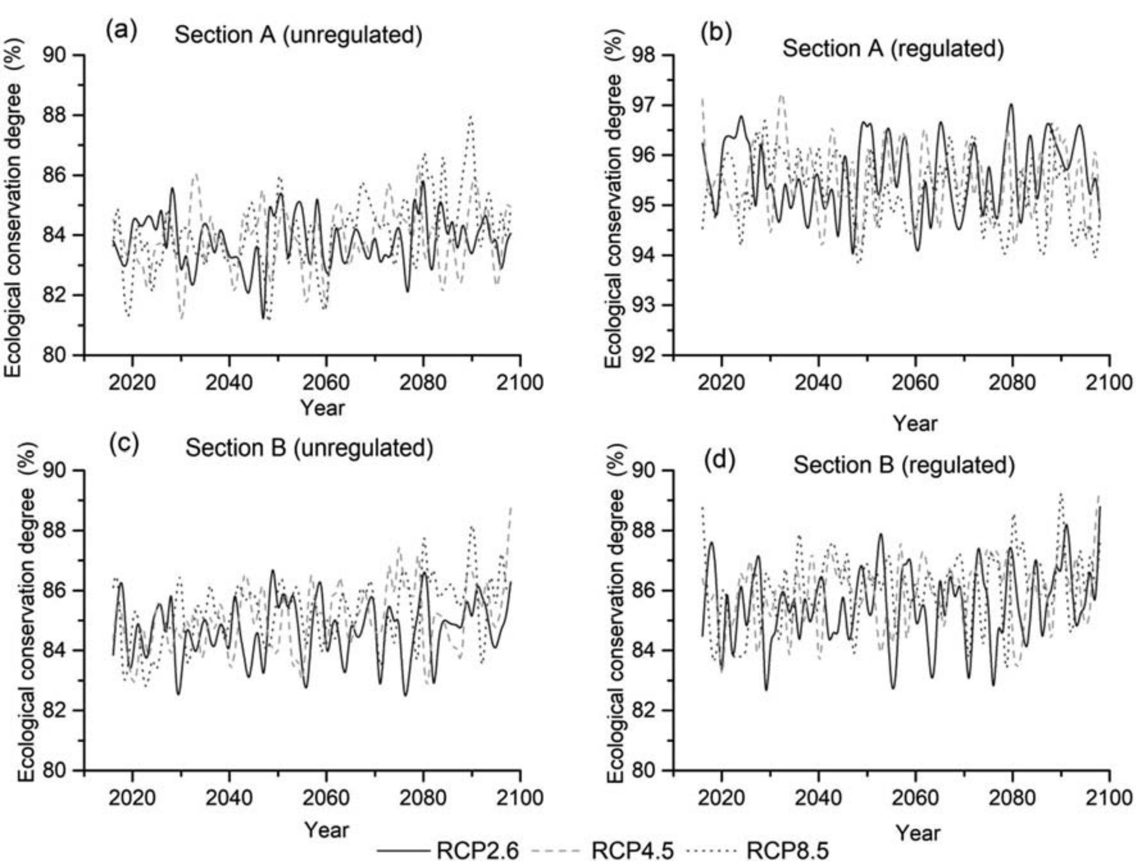

Fig. 10. Future annual ecological conservation degree (%) of the Yuan River basin before and after cascade dam construction in 2015–2100 under RCPs 2.6, 4.5 and 8.5, respectively. (a) Unregulated condition of Section A; (b) regulated condition of Section A; (c) unregulated condition of Section B; and (d) regulated condition of Section B.

The upper and lower limits of ecological discharge at a 70% ecological conservation degree were plotted. In Section A where is the representative habitat of *Cyprinus rubrofuscus* Lacépède, the ecological discharge for the 70% ecological conservation degree cannot be guaranteed under unregulated conditions in April (breeding period) and July–August (growth period) of both 1951–2010 and 2015–2100. The monthly runoff is slightly lower than the lower limit in April (dry season), and higher than the upper limit of in July and August (flood seasons), with an increase of 7.98% in 1951–2010 and 24.30–31.16% in 2015–2100 due to intensified ecological destruction. The regulation by Jiasajiang and Qiaotou reservoirs leads to a more controlled discharge in July and August and an increase of discharge in April (growth stage of *Cyprinus rubrofuscus* Lacépède). As a consequence, the required ecological discharge in 1951–2010 and 2015–2100 can be guaranteed, and habitat quality can be significantly improved. In Section B where is the representative habitat of *B. rutilus*, the ecological discharge at a 70% ecological conservation degree can be satisfied in 1951–2010, but the mean runoff is lower than the lower limit of ecological discharge from April to May (spawning period) in 2015–2100. However, reservoir regulation leads to a slight increase in discharge from April to May, which is beneficial for spawning. However, the effect is not sufficiently large due to the limited reservoir regulation capacity, and the minimum ecological discharge cannot be reached.

4.3.2. Prediction of fish habitat sustainability

Fig. 10 shows changes in future annual ecological conservation degree before and after cascade dam construction. Under the conditions of no reservoirs, the mean annual ecological conservation degree of Section A in 2015–2100 fluctuates between 81.8 and 86.5% with no clear trend. The regulation by Jiasajiang reservoirs leads to an increase in runoff in dry seasons from January to January and impounding occurs from August to September, resulting in an increase in ecological discharge for the spawning of *Cyprinus rubrofuscus* Lacépède and reduces the impacts of large discharge on fish habitat in flood seasons. As a result, the habitat quality in Section A is significantly improved under cascade dam construction, and the ecological conservation degree ranges from 93.5–97.7%. Under the conditions of no reservoirs, the mean annual ecological conservation degree of Section B in 2015–2100 fluctuates between 82.35 and 88.99%, with no clear trend but a lightly higher fluctuation amplitude than that of Section A. The spawning period of *B. rutilus* is from April to July, and the growth period is from November to March of the next year. Thus, the discharge of Nansha and Madushan reservoirs is slightly decreased from November to December and increased from March to April, resulting in an ecological conservation degree of 82.94–90.79%. Again, the habitat quality is not sufficiently improved due to the limited regulation capacity.

Fig. 11 shows the future monthly ecological conservation degree of the Yuan River basin. Under the unregulated conditions, there is a large fluctuation in the future monthly ecological conservation degree in Section A, which is low in March, April, May, August and November. In the spawning period of *Cyprinus rubrofuscus* Lacépède from March to May, the mean monthly runoff is close to the lower limit of the ecological discharge at a 70% ecological conservation degree, making it difficult to ensure the spawning of *Cyprinus rubrofuscus* Lacépède. In the growth stage (August) of *Cyprinus rubrofuscus* Lacépède in which the runoff reaches a maximum, the mean runoff is 27.3% higher than the upper ecological limit, which is detrimental to fish habitat and fish growth. In the breeding season (November) of *Cyprinus rubrofuscus* Lacépède, in which the flood season is just finished, there is a sharp decrease in runoff, which is detrimental to the breeding of *Cyprinus rubrofuscus* Lacépède. After reservoir regulation, the ecological conservation degree in each month is significantly improved in Section A. It

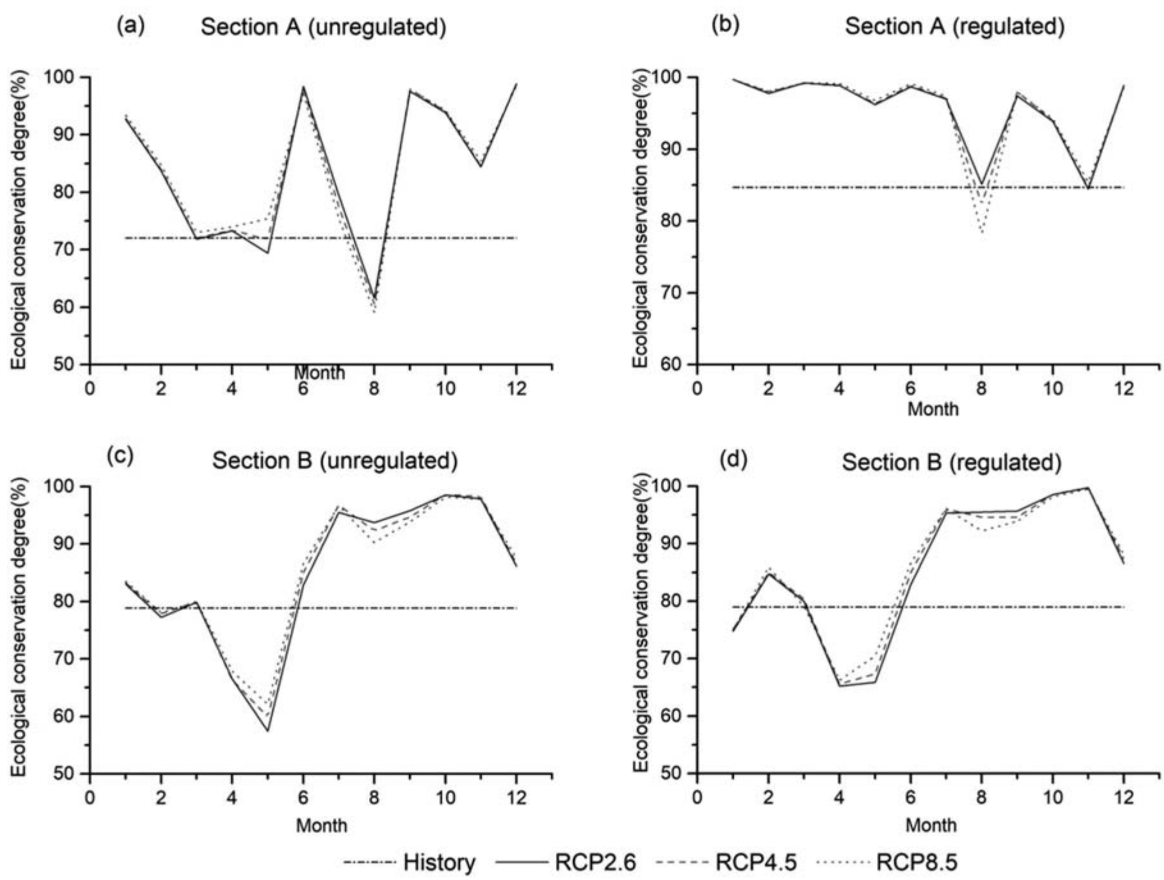

Fig. 11. Monthly ecological conservation degree (%) of the Yuan River basin from 2016 to 2100 under RCP2.6, RCP4.5 and RCP8.5 respectively. (a) Unregulated condition of Section A; (b) regulated condition of Section A; (c) unregulated condition of Section B; and (d) regulated condition of Section B.

is above 95% on average, but as low as 78.32–85.09% and 85% in August and November, respectively. In August, the discharge is high even after reservoir regulation due to abundant rainfall in this period, resulting in a potential effect on fish growth. In November in which the runoff is decreased sharply, reservoir regulation results in only a slight increase in flow rate, which is sufficient for fish breeding.

Under no cascade development, Section B shows a high level of ecological conservation degree (>85%) from June to December, but a low level (60–70%) from April to May. In non-flood seasons from January to May, the runoff fluctuates around the lower limit of the ecological rate at a 70% ecological conservation degree. In particular, the runoff in April and May is 7.4% and 22.17% lower than the lower limit, respectively, which is detrimental to the spawning of *B. rutilus*. The reservoir regulation results in no obvious change in the general pattern. However, the runoff from April to May is higher than the lower limit, resulting in an improvement of habitat quality by about 5%.

5. Discussion

The effects of different factors on the runoff of the Yuan River basin are shown in Fig. 12. It is clear that reservoir operation has a significant effect on runoff, and the relative change rate of Section A is much higher in March and April than that in other months. This is because there is less natural runoff in non-flood seasons in March and April, the reservoir releasing amount is 2.8 times the natural streamflow, resulting in a significant change in original runoff. In other non-flood seasons, despite the small flow rate, only a small amount of water is retained by the reservoir, resulting in a slight decrease in runoff and consequently a slightly lower relative change rate. In general, the relative change rate is higher under RCP4.5 than that under RCP8.5. The construction of cascade dams results in a small difference in the change of monthly runoff between RCP4.5 and RCP8.5, but a higher fluctuation of runoff with a discrete distribution under RCP8.5. In Section B, the reservoir is mainly used to impound water in dry seasons from January to March, resulting in a reduction of runoff by approximately 40 m^3/s and thus a larger relative change rate than that in other months.

Under the influence of climate changes, the relative change rate of the runoff of Section A is higher than 1 only in April, because the runoff sequences are more stable and concentrated in April than in other months with a variance of 7.51. The natural runoff of Section B in 2015–2100 is changed by <20 m^3/s compared with that in 1951–2010, with a stable relative change rate of <1 in each month. Under different RCP conditions, there is a small change in the relative change rate of runoff, but the annual runoff shows an increasing trend over time. As a result, the relative change rate shows an obvious increasing trend in relative to that in 1951–2010, indicating that climate changes have an increasingly important effect on runoff. However, it is important to note that climate changes have a less significant effect than cascade reservoir development on runoff, with a relative change rate of <1 in most cases.

Under the combined influence of climate changes and cascade development, the annual pattern of runoff relative change rate of Section A is similar to that under the influence of only cascade development. The relative change rate increases from January to April and is much higher than that in other months. It fluctuates around 1 from May to December. However, the relative change rate of runoff from January to August is decreased by 7.75 on average compared with that under only cascade development, which is especially pronounced from February to April with a decrease of up to 60%. The relative change rate from September to December is increased slightly, and the increase rate is similar to that under only climate changes. To sum up, the change of runoff from January to August is determined mainly by cascade

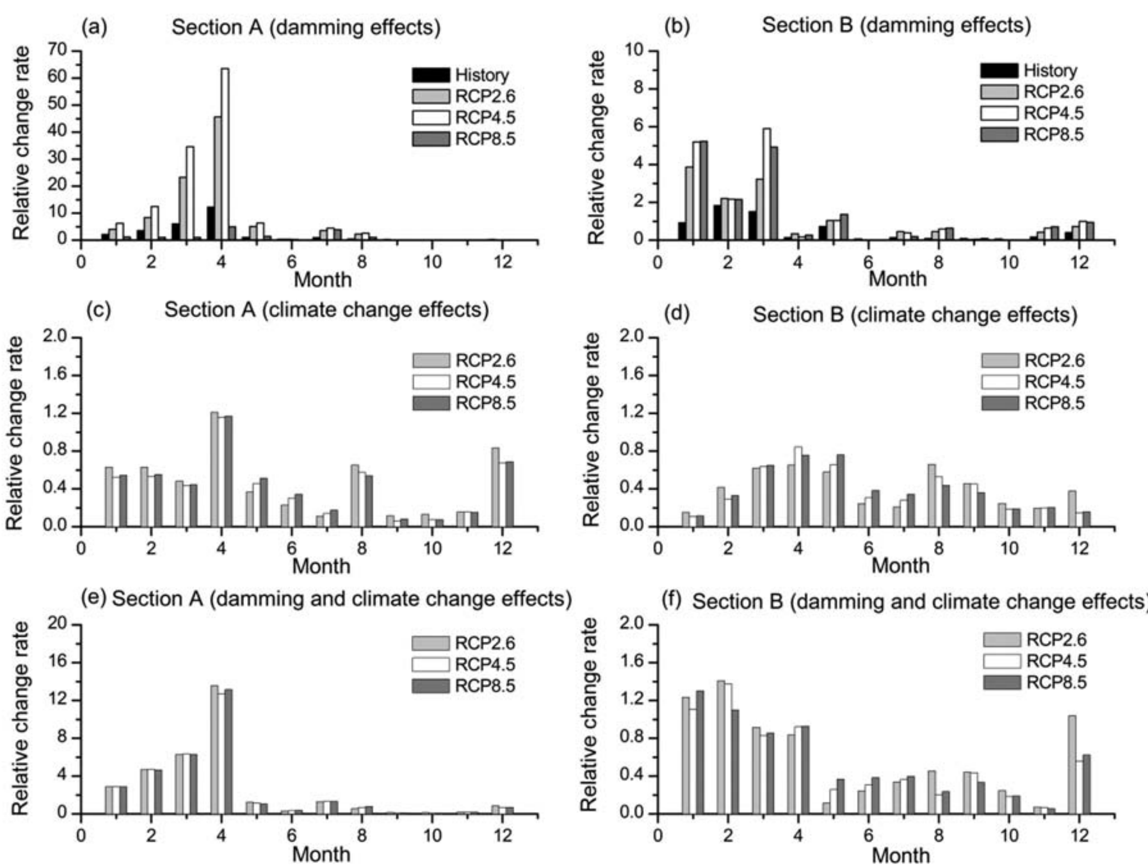

Fig. 12. Monthly relative change rate of runoff in the Yuan River Basin. (a) damming effects of Section A; (b) damming effects of Section B; (c) climate change effects of Section A; (d) climate change effects of Section B; (e) cumulative effects of Section A; (f) cumulative effects of Section B.

development, and the releasing is increased in dry seasons from September to December to ensure the survival and growth of fish. As a result, the runoff reaches a level close to that in 1951–2010 and thus the influence of climate changes becomes more pronounced. However, the relative change rates of Section B are more uniformly distributed and lower than that of Section A. The distribution pattern of the relative change rate of Section B is close to that under only cascade development, and the range is close to that under climate changes. The relative change rate is high (0.8–1.4) from December to April of the next year, but low (<0.5) from May to November. In general, cascade development has an effect on runoff of Section B only in dry seasons due to the limited regulation capacity of reservoir, and climate changes have an effect on runoff in wet seasons.

The effects of different factors on fish habitat quality in the Yuan River basin are shown in Fig. 13. Under the influence of cascade development, there is a strong relationship between the relative change rate of ecological conservation degree and runoff in Section A. The relative change rate increases in dry seasons from January to April and is higher than that in other months, resulting in poor fish habitat quality under natural conditions. The construction of cascade dams results in an increase in discharge from the Jiasajiang reservoir from January to April, which could improve spawning and ecological conservation degree. In flood seasons, especially from July to September, the major objective of reservoir operation is flood control, resulting in no significant improvement of habitat quality. Although runoff decreases from October to December, the habitat quality is good and thus reservoir operation shows no significant effect. In Section B, cascade development has a particularly pronounced effect on ecological habitat quality in January, February, March and May, with a change rate of about 6.5 in January. However, climate changes have a less significant effect on fish habitat quality in other months.

Under climate changes, the change rate of ecological conservation degree of Section A is high in April and December but fluctuates around 1 in other months, and it is generally lower than that under cascade development. The change rate of ecological conservation degree in Section B is high in dry seasons but low in flood seasons. Climate changes have a more significant effect on fish habitat quality from February to May and from September to December than cascade development. The climate change effect in Section B is lower than that in Section A.

Under climate changes and cascade development, the distribution patterns and ranges of the relative change rates of the ecological conservation degrees of both Section A and Section B are close to that under climate changes. They have a pronounced effect on Section A in April, with a change rate of 8.08; a minor effect in June with a change rate of <0.5; and a moderate effect in other months with a change rate of approximately 1. The habitat quality of Section B shows a uniform change in the range of 1–3. In flood seasons, cascade development and climate changes alone have a minor effect on fish habitat quality in Section B, but they have a significant combined effect. In general, climate changes have a long-term and increasingly significant effect on fish habitat quality. However, cascade reservoir operation considering ecological conversation could result in a slight increase in ecological conservation degree in dry seasons but no damage to fish habitat. In comparison, climate changes have a more significant effect on fish habitat in the Yuan River in the future.

6. Conclusions

In this study, we investigated the potential future changes in stream flow and fish habitat quality in the Yuan River, and assessed the

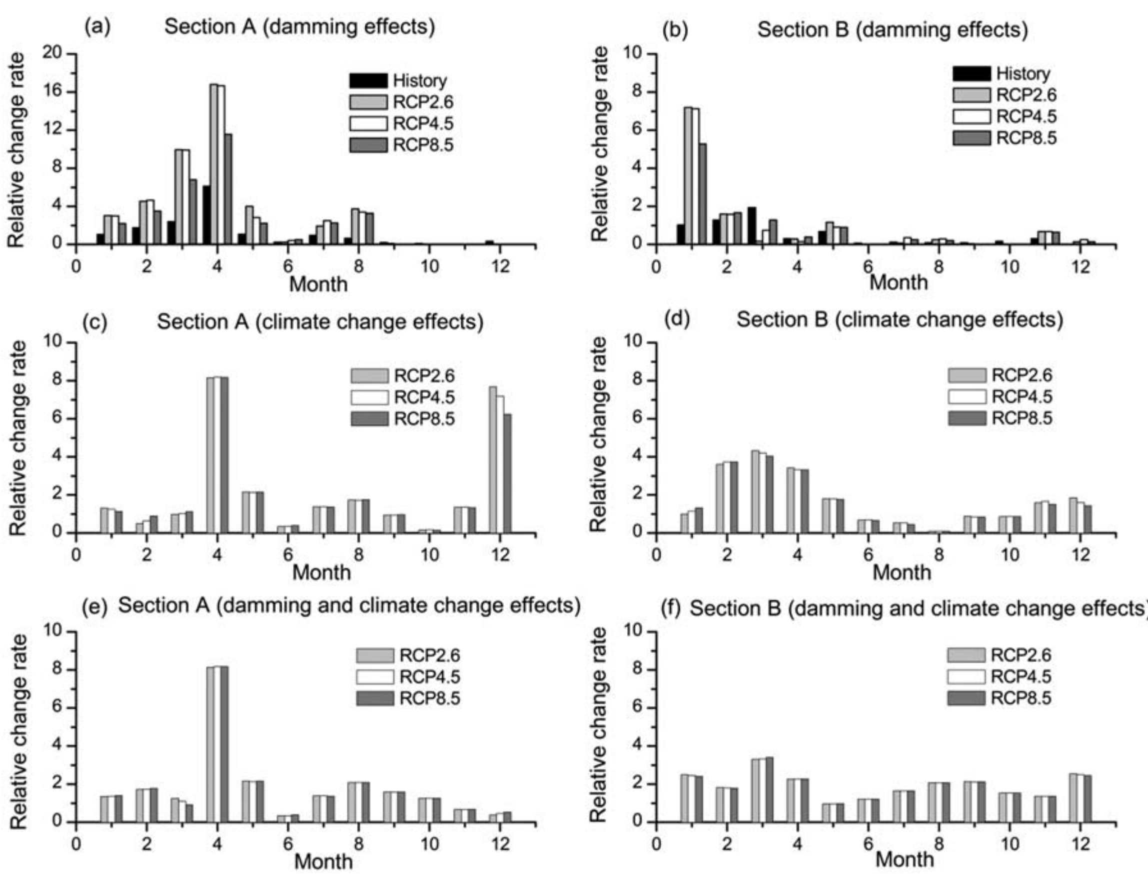

Fig. 13. Monthly relative change rate of ecological conservation degree in the Yuan River Basin. (a) damming effects of Section A; (b) damming effects of Section B; (c) climate change effects of Section A; (d) climate change effects of Section B; (e) cumulative effects of Section A; (f) cumulative effects of Section B.

individual and combined effect of cascade reservoir development and climate change. The main conclusions are summarized as follows:

(1) The mean annual temperature in 2015–2100 is increased by 1.31–2.60 °C relative to that in 1951–2010. The annual precipitation in 2015–2100 is increased by 2.53–4.74% relative to that in 1951–2010. Temperature and precipitation are sensitive to radiation intensity, and they increase significantly with the increase of radiation intensity.

(2) The mean annual runoff in 2015–2100 indicate a variation of 0.69–6.98% for Section A and − 0.96-5.69% for Section B in relative to that in 1951–2010, respectively. There is a frequent alternation between wet and dry years. Under no regulated conditions, the future natural runoff of Section A and Section B will possibly increase by 0.83–5.46% and 3.2–11.15% relative to that in 1951–2010, respectively. The cascade development can reduce the difference in runoff between dry and wet years. Similarly, it is also sensitive to radiation intensity and increases with increasing radiation intensity.

(3) The habitat quality in Section A is significantly improved under cascade dam construction. The monthly ecological conservation degree is above 95% on average, but as low as 78.32–85.09% and 85% in August and November, respectively. No significant improvement is obtained in fish habitat quality for Section B. However, April and May (worst ecological periods in history) would see an improvement in habitat quality by about 5%.

(4) The construction of cascade dams brings about a significant change in runoff, with a higher relative change rate in March and April than in other months. The relative change rate of Section B is large from January to April. Climate changes have a less significant effect than cascade reservoir development on runoff, with a relative change rate of <1 in most case. However, climate changes have an increasingly important effect on runoff over time. Under the combined influence of climate changes and cascade development, the runoff change of Section A from January to August is determined mainly by cascade development, and the influence of climate changes becomes more pronounced in dry seasons from September to December. Cascade development has an effect on runoff of Section B only in dry seasons due to the limited regulation capacity of upstream reservoir, and climate changes have an effect on runoff in wet seasons.

(5) The construction of cascade dams have a more significant impacts on fish habitat quality from January to April for Section A and January to March and May for Section B, respectively. Climate changes have a significant effect on fish habitat quality in April and December for Section A, and it is generally lower than that under cascade development; whereas the climate change impacts on Section B is high in dry seasons but low in flood seasons, and the effect is particularly more pronounced than that of hydropower development. Under climate changes and cascade development, the distribution patterns and ranges of the relative change rates of the ecological conservation degrees of both Section A and Section B are close to that under climate changes. Climate changes have a more significant effect on fish habitat in the Yuan River in the future.

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